Development of a Peristaltic Crawling Inspection Robot for Half-Inch Pipes Using Pneumatic Artificial Muscles

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Abstract: This paper describes the development of an in-pipe inspection robot for use in half-inch pipes. Half-inch pipes are commonly used in factories and residences, and in-pipe inspection is essential for preventing accidents caused by burst pipes or corrosion. In-pipe inspection is currently endoscopically conducted; however, endoscopes cannot be inserted into pipes that are more than 15 m long or that have complex shapes, such as elbows. Therefore, various in-pipe inspection robots have been developed, though very few can travel inside half-inch pipes, and none can pass through a 90° elbow. Moreover, no study reports in-pipe robots making long-distance runs within half-inch pipes. The authors have developed a peristaltic crawling inspection robot with pneumatic artificial muscles for use in half-inch pipes; they seek to enable the robot to pass through a 90° elbow and have studied the robot’s ability to travel long distances of more than 15 m.

Key Words: pipe inspection, earthworm, peristaltic crawling, pneumatic, artificial muscle.

1. Introduction

The objective of this study is the development of an in-pipe inspection robot that can inspect long distances within half-inch pipes.

Half-inch pipes are commonly used in factories and residences. At present, inspection of gas pipes for residences is especially important. In-pipe inspection is essential to prevent accidents caused by pipe bursts or corrosion, and is currently endoscopically conducted. However, endoscopes cannot be inserted into pipes that are more than 15 m long or that have complex shapes, such as elbows, because they eventually deflect and fail to penetrate further. To solve this problem, various in-pipe inspection robots have been developed. However, these robots have drawbacks. For example, snake-like robots [1] require a large space for moving, and it is difficult to reduce wheel-type robots’ size [2]–[4] because of their complex structure; therefore, these types of robots are not suitable for moving in narrow pipes. In addition, a robot with ciliary vibration mechanisms [5] cannot move backward nor climb vertically. Very few in-pipe robots that can travel inside half-inch pipes have been developed, [6] and none can take videos of the insides of pipes. Moreover, no study reports the use of robots that can pass through a 90° elbow, whose radius of curvature is equal to its inside diameter (Rc = 1.0 inner diameter (ID)), nor are there any reports of in-pipe robots traveling long distances within half-inch pipes.

However, the authors have already studied robots that emulate the peristaltic crawling of an earthworm [7]–[12]. An earthworm’s peristaltic crawling requires little room for motion and its area of ground contact is large. Therefore, the robot is able to move stably in narrow pipes, such as half-inch pipes.

The authors have developed the peristaltic robot for half-inch pipes driven by pneumatic actuator [10]. In this report, we confirmed that the maximum speed of this robot was about 480 mm/min and the Maximum tracking force was about 12 N. Thus, this type robot has enough ability to lead the cable of 15 m. However, since the long air tube (over 10 m) wasn’t used, the delay of response due to the pressure propagation in the air tube has not been adequately verified. Further, this robot didn’t have a function to pass through the elbow.

Thus, in this paper, we develop a peristaltic crawling robot for half inch pipes that can pass through the elbow and travel long-distance pipe. First of all, some experiments on the basic performance of the robot, such as driving speed and propulsive force are performed. Furthermore, they seek to enable the robot to pass through a 90° elbow (Rc = 1.0). In addition, by applying the long-range air tube to the robot, the influence of the delay of the pressure response is discussed.

2. Peristaltic Crawling of Earthworms

Peristaltic crawling is used by life forms such as earthworms and inchworms for moving forward. The robot developed in this paper emulates the earthworm’s motion. An earthworm consists of 110–200 segments. Figure 1 (a) shows the structure of an individual segment. The earthworm has two muscle layers: a circular muscle that is arranged inside of a skin circumferentially, and a longitudinal muscle that is arranged inside the circular muscle in the axial direction. The former elongates and the latter contracts the segments in the axial direction [13]. Figure 1 (b) shows the earthworm’s peristaltic crawling pattern. The earthworm contracts and expands as follows:

(1) The earthworm contracts an anterior segment using the longitudinal muscles.

(2) This contraction is transmitted to rear segments while the anterior segments are elongated by the circular muscles simultaneously.
(3) The contraction segments generate frictional force between the segments and a surface. Because of this frictional force, a reaction force to elongate contraction segments is generated.

Thus, the earthworm can move because of the repetition of thick-short and thin-long motion.

Fig. 1 Peristaltic crawling pattern of an earthworm.

3. Straight-Fiber Artificial Muscle

A straight-fiber artificial muscle as the actuator for the robot was used [14]. Figure 2 shows an overview of the artificial muscle, which is made of low-ammonia natural-rubber latex and micro-carbon fiber. This construction offers the following advantages: lightness, low price, flexible, and high output force and contraction ratio. The materials are formed in a tube, and a micro-carbon sheet is inserted into the tube in the long-axial direction. The range of the sheet extends when the rubber elongates [15].

This actuator is controlled by air pressure. When air is supplied to the actuator, the artificial muscle contracts in the axial direction and expands in the radial direction because the film expands but the carbon sheet maintains its shape.

Fig. 2 Straight-fiber artificial muscle.

Table 1 Unit specification.

| Mass (g) | 1.60 |
| Length (mm) | Extension | 28.0 | Contraction | 26.5 |
| Width (mm) | Extension | 10.0 | Contraction | 18.0 |

4. Peristaltic Crawling Inspection Robot for Half-Inch Pipes

4.1 Outline of Robot

Figure 3 shows an image of the robot, which consists of six units, five joints, and a head section, which guides the robot when it passes through an elbow. The robot weighs 33 g and has a length of 360 mm when fully extended. As stated earlier, this robot was developed by emulating the motion of an earthworm. Each unit is equal to a segment of an earthworm. Each unit contracts and extends in the axial direction. Therefore, this robot repeats the extension and contraction motion in the same way as an earthworm’s motion.

Fig. 3 Peristaltic crawling inspection robot.

4.2 Unit for Robot

Figure 4 shows an image of a unit and Table 1 shows the specifications. A unit consists of two flanges, aluminum sheet and silicon tape-coated compression spring, and artificial muscle. An air tube is 2 m long.

When air is supplied to the chamber, the artificial muscle contracts in the axial direction and expands in the radial direction. When air is discharged from the chamber, the artificial muscle extends in the axial direction.

Fig. 4 Configuration of the unit.

4.3 Head Section

In this section the requirement for the head section to guide the robot is explained when the robot is passing through an elbow. A large step exists at the part of connection between an elbow and a straight pipe. It is difficult for this type robot to pass through because the head section often cannot climb over the steps. Figure 5 shows an image of the head section climbing over. First, to climb over the step, the hemi-spherical part of the head section needs to proceed in the direction of travel. However, if the head section is not flexible, the head section cannot climb over and the robot also cannot proceed. Therefore the tip of the head section needs to be flexible. Figure 6 shows an image after the head section has climbed over the step. If the head section is flexible, the base of the head section buckles, therefore the head unit collides with the elbow. Thus, the base of the head section needs a pulling force that pulls it backward because the head unit needs to proceed in the direction of traveling.

Fig. 5 Climbing over.

Table 1 Unit specification.

| Mass (g) | 1.60 |
| Length (mm) | Extension | 28.0 | Contraction | 26.5 |
| Width (mm) | Extension | 10.0 | Contraction | 18.0 |

Figure 7 shows an image of the head section. This head section consists of a hemispherical part and extension spring. The hemispherical part is hollow to allow an endoscope to be attached. The tip of this extension spring is extended like compression spring in order to become flexible. Therefore, this
head section climbs over the step using the flexibility of the tip of this head section, and pulls itself backward by using the pulling force of the extension spring by sliding on inner the straight pipe.

Fig. 5 Head section climbing over a step.

Fig. 6 Image after the head section has climbed over the step.

Fig. 7 Head section.

4.4 Joint of the Robot

Figure 8 shows an image of the joint. This joint connects units to enable the robot to bend as it passes through an elbow. This joint consists of a natural rubber tube and a compression spring and has a length of 25 mm and an outer diameter of 8 mm.

Fig. 8 Joint of the robot.

4.5 Operation System

Figure 9 shows the robot’s control system. The robot is controlled by a H8-3052F microcomputer. Digital signals output from the H8 microcomputer are converted into analog signals using a digital-analog converter. These analog signals are then input to a proportional solenoid valve. The air pressure that is supplied to the robot via a manifold from a compressor is proportional to the input voltage. Thus, the units are free to extend and contract independently.

Fig. 9 Control system of the pneumatic robot.

4.6 Motion Patterns

By altering the extension or contraction of each unit, several motion patterns can be achieved. Motion patterns consist of a wavelength, propagation speed, and waves. Here, wavelength is the number of units extended in the axial direction. The propagation speed is the number of units propagated in the rear. Here \( l, s, n \), and \( N \) are the wavelength, propagation speed, number of waves, and number of units, respectively. Henceforth, the basic motion patterns is identified as motion \( l-s-n \). For example, motion 4-1-1 (wavelength–propagation speed–number of waves) is shown in Fig. 10. Each of the parameters must satisfy the following equations:

\[
(l + s)n < N. \\
N - l > s. \\
l \geq s.
\]

Fig. 10 Motion pattern 4-1-1.

5. Traveling Performance of the Robot

To examine the fundamental performance of the robot using the short length tubes, some experiments are carried out. In this section, the driving speed in the straight pipe, propulsive forces of the robot and driving experiments of the elbow are discussed.

5.1 Driving Speed in a Straight Pipe

The robot’s driving speed was measured. These experiments were conducted in a horizontal, straight, half-inch acrylic pipe, whose inside diameter was 16 mm. Motion patterns 2-1-1, 3-1-1 were used, and 4-1-1 and air pressure of 0.1 MPa is applied to the unit. We changed the time interval from 0.1 s to 0.5 s at 0.1 s intervals for sending signals to contract a unit were used.

Figure 11 shows the experimental results. From these results, we observe that the robot’s maximum driving speed is 426 mm/min with motion pattern 4-1-1 and a time interval of 0.1 s. The driving speed increases with the wavelength; we think this is because the robot’s contraction amount in one motion cycle increases with the wavelength. In addition, the driv-
ing speed increases with a decrease in the time interval; we think this is because the time of one motion cycle decreases.

![Graph showing driving speed in a half-inch pipe.](image1)

**5.2 Propulsive Force of the Robot**

Propulsive force is needed when the robot passes through shapes such as elbows. Figure 12 shows the experimental environment for measuring propulsive force. The robot moved forward in the horizontal, straight, half-inch acrylic pipe, and collided with a load cell. Therefore, the propulsive force was measured by the load cell.

Motion patterns 2-1-1, 3-1-1 were used, and 4-1-1 and air pressure of 0.1 MPa was applied to the unit. The time interval from 0.1 s to 0.4 s at 0.1 s intervals were changed.

![Experimental environment for measuring propulsive force.](image2)

Figure 13 shows the experimental result. From the result, we observe that the robot’s maximum propulsive force is 3.7 N with motion pattern 2-1-1 and a time interval of 0.4 s. The propulsive force increases with an increase in time interval because the extension force of the unit approaches its maximum value when the time interval increases. In addition, the propulsive force increases with a decrease in the wavelength; we think this is because the robot’s friction force increases by increasing the number of expansion unit when the wavelength decreases.

![Graph showing experimental results of propulsive force.](image3)

**5.3 Driving Experiment in an Elbow**

90° elbow (Re = 1.0 ID) are frequently encountered in real-life environments. Therefore, in-pipe robots that can pass through such elbow is needed. However, there are no reports of robots passing through half-inch elbows. Thus, we conducted an experiment to investigate whether our developed robot can pass through a 90 degrees elbow.

Figure 14 shows the half-inch elbows used in the experiment, which was conducted in the horizontal, straight, half-inch acrylic pipe and associated elbows. Motion patterns 2-1-1, 3-1-1 were used, and 4-1-1 and air pressure of 0.1 MPa is applied to the unit. The time interval from 0.1 s to 0.5 s at 0.1 s intervals are changed.

![Elbow](image4)

Figure 15 shows the experimental result. From the result, we observed that the robot passed through the elbow with motion pattern 3-1-1 and time interval of 0.4 s. The robot passed through the elbow in 438 s (With other motion pattern, the robot could not pass through it in 700 s); therefore, the robot’s average driving speed was 54 mm/min in the elbow—less than the robot’s driving speed of 90 mm/min in a straight pipe. We believe the reasons for this are as follows:

1. Because the joints of the robot pushes on inner wall of the elbow, when the joints pass through the elbow, friction force increases between the joint and the pipe. Hence the robot cannot pass through smoothly.

2. Depending on the motion pattern, the expansion unit is in the elbow cannot hold the walls; therefore, the robot sometimes moves back and forth in the elbow.

3. As shown in Fig. 15 from (4) to (5), if there are the expansion units that are held to the inner wall of the straight pipe after passing through the elbow, the robot can move forward. On the other hand, there may not exist the expansion units, depending on the motion pattern. In this case, the robot is likely to retract.

To solve these problems, reduction of the robot’s friction surface and changing the robot’s motion pattern as it passes through the elbow are needed.

**6. Application to Long-distance Run—Basic Study on Lengthening the Air Tube—**

Endoscopes cannot inspect pipes more than 15 m long. To enable the robot to inspect pipes more than 15 m long, A basic study on lengthening the air tube was conducted.

**6.1 Experiment of Pressure Response and Air Tube**

We conducted this experiment to confirm whether the pressure response changed when changing the air tube length. Air
Fig. 15 Robot in a half-inch horizontal elbow.

Fig. 16 shows experimental results of pressure response and air tube length when the input air pressure is 0.12 MPa. In addition, Fig. 17 shows the rise time of each pressure response. From the results, we confirm the following:

1. From Fig. 16, regardless of the length of the pipe, the steady-state value of air pressure is almost constant under a same input pressure.

2. From Figs. 16 and 17, the rise time of air pressure response is increased with increasing length of pipes. Further, depending on the increase in input pressure, pressure response is improved.

Here, if the supplied air pressure increases, it is predicted that the fall time of air pressure response decreases because amount of the air in unit is increasing with increasing air pressure.

6.2 Experiment of Unit Contraction Response with Step Input using a Long Air Tube

In Section 6.1, we confirmed that the pressure response changed by changing the air tube length. If we lengthen the air tube from the current length of 2 m, the air pressure response becomes delayed and the contraction response of the unit possibly will change as well. Therefore, measurement the unit’s characteristics considering air tube length and determination the robot’s optimal driving conditions are needed.

In this section, we confirm whether the contraction response of the unit changes by changing the air tube length. If the response of the unit changes, the optimal air pressure value was determine.
Figure 18 shows the experimental environment for measuring the contraction response of the unit. One side of the half-inch acrylic pipe and the unit was fixed to a laser displacement meter; the other side of the unit was fixed to a movable plate. From this state, we applied air pressure to the unit and used the laser displacement meter to measure the amount of the axial direction displacement of the movable plate. We used 1 m and 20 m long air tubes (ID is 1.2 mm; OD is 1.8 mm and made of urethane).

Figure 19 shows an example of the experimental results. From the results, we confirm that the contraction response of the unit changes with the changes in the air tube length.

Figure 20 shows the amount of the unit’s contraction with a 1 m and 20 m air tube. Here, the expanded diameter of the unit from the amount of unit contraction is calculated. The expanded diameter of the unit $d_m$ (mm) is expressed as

$$d_m = \alpha \sqrt{r l_0} + d_0.$$  

Here, $l_0$ and $d_0$ are the natural length and diameter (in mm) of the artificial muscle, respectively. $r$ is the amount of unit contraction. Moreover, $\alpha$ is the value that depends on the size and diameter of the artificial muscle, and $\alpha = 1.1$ in the robot’s artificial muscle. More detail on Eq. (4) is available from references [16]. Figure 21 shows the expanded diameter of the unit, which is calculated by substituting the amount of unit contraction into Eq. (4). From the values shown in Figs. 20 and 21, we confirm that the amount of contraction and the expanded diameter of the unit do not change with changes in the air tube length. Furthermore, we confirm from the values in Fig. 21 that we need to apply an air pressure of more than 0.09 MPa to the unit because the diameter of the unit becomes greater than the ID of the half-inch pipes that are 16 mm in length, and the robot can hold the pipes.

Figures 22 and 23 show the rise and fall times of the contraction response of the unit with 1 m and 20 m tubes, respectively. From the values shown in Figs. 22 and 23, we confirm that the rise and fall times are delayed by more than 1 s if the air tube length changes from 1 m to 20 m. Moreover, the rise and fall times of the 20 m air tube are quickest (1.07 s and 1.26 s, respectively) when the applied air pressure is 0.12 MPa. Therefore, with the 20 m air tube, the optimal air pressure value is determined as 0.12 MPa.

6.3 Experiment of Unit Contraction Response with Pulse Input using a Long Air Tube

In Section 6.2, the contraction response of the unit with step input was confirmed. However, when the robot actually travels, the air pressure to the unit with pulse input is applied. Therefore, in this section, the contraction response of the unit with pulse input and a 20 m air tube is confirmed. In addition,
Fig. 23 Relationship of rise time, fall time, and pressure (air tube length 20 m).

robot’s predictive driving speed is calculated when it is used with a 20 m air tube.

The experimental environment is the same as that illustrated in Fig. 18. Taking air pressure loss into consideration, the input pressure of 0.16 MPa is applied to the unit through a 20 m air tube. Here, the input pressure was adjusted so that the internal pressure of the unit is 0.12 MPa. The experimental results using motion pattern 3-1-1 and a time interval of 0.5 s are shown in Fig. 24. As shown in Fig. 24, the unit repeats its extension and contraction motion and the diameter of the unit reaches the ID of the pipe. Therefore, we believe that the robot can move forward in the pipes when used with a 20 m air tube.

Here, the experimental results was used to calculate the robot’s predictive driving speed with a 20 m air tube. The robot’s predictive driving speed \( v_{mn} \) (mm/s) is expressed as

\[
v_{mn} = \frac{r \cdot n \cdot \lambda}{N \cdot t}
\]

Here \( \lambda \), \( s \), \( n \), and \( N \) are the wavelength, propagation speed, number of waves, and number of units, respectively. \( r \) is the amount of the unit’s contraction (in mm), and \( t \) is the time interval (in s). \( m \) is the division number of the robot’s extension and contraction motion. More detail on Eq. (5) can be found in references [11]. When we substitute the experimental results shown in Fig. 24 in Eq. (5), the robot’s predictive driving speed \( v_{mn} = 51 \text{ mm/min} \) is obtained when using motion pattern 3-1-1 and a time interval of 0.5 s.

6.4 Experiment of Driving Speed using a Long Air Tube

We measured the driving speed of the robot with a 20 m air tube and compared it with the driving speed of the robot with a 2 m air tube. These experiments were conducted in a horizontal, straight, half-inch acrylic pipe whose inside diameter was 16 mm. Motion patterns 3-1-1 and 4-1-1 were used and air pressure of 0.16 MPa is applied to the unit. The time interval was changed from 0.3 s to 0.5 s at 0.1 s intervals.

Figure 25 shows both the experimental driving speed and the predictive driving speed calculated from Eq. (5). From the results shown in Fig. 25, we confirm that the robot can travel in a half-inch pipe when the air tube length becomes 20 m; however, the experimental value is slower than the predictive value. We believe there are two reasons for this difference. The predictive value is calculated from the contraction response of one unit, but the robot comprises several units; therefore, there are variations in unit contraction responses with individual artificial muscles. In addition, when the robot actually travels, the robot’s joints are affected by force from anteroposterior units, friction between the robot and pipe, and return by the elasticity of the rubber; therefore, the joints contract.

Figures 26 and 27 show the experimental results of the driving speed in both 20 m and 2 m air tubes, respectively. From those results, we observe that the maximum driving speed of the robot with a 20 m air tube is 66 mm/min with motion pattern 4-1-1 and a time interval of 0.4 s. This driving speed is slower than that with a 2 m air tube because both the air pressure response and the unit contraction response are delayed as the air tube grows in length.
7. Conclusions and Future Work

7.1 Conclusions

The peristaltic crawling robot for in-pipe inspection of half-inch pipes using pneumatic artificial muscles was developed. Our results are as follows:

1. The robot can pass through a half-inch elbow.
2. The air tube to 20 m to apply the robot to long-distance runs and determined that the optimal air pressure value for the robot is 0.12 MPa.
3. The robot can travel in a half-inch pipe with a long (20 m) air tube.

7.2 Future Work

To increase the robot’s driving speed, we should conduct two provisions:

1. To reduce the unit’s contraction time, we should use a method that applies high pressure to the unit instantaneously.
2. To reduce the unit’s extension time, we should either place the air discharge hole inside the unit or use a method that aspirates air with negative pressure.

Moreover, we should construct a mathematical model that shows the relation between air tube length and unit response characteristics, using the air pressure response model [17] as a reference. In addition, it is planned to apply the present robot to 15 m or more pipes, including the elbow.

References


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